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1.0 STATEMENT

Surface Optics Corporation (SOC), in association with UC Irvine, Department of Physics, has been conducting a combined theoretical and experimental research program on the unconventional optics for "Temporal and Spectral Coherence from Rough Surface Scattering". The program covers a three year period. The analytical phase of the investigation is complemented by an experimental effort and the fabrication of one- and two-dimensional surfaces with controlled statistics.

The enhanced backscattering is manifested by the presence of a well-defined peak in the retro-reflection direction in the angular distribution of the intensity of the diffusely scattered light from a rough surface. We have shown enhanced backscattering at grazing angle, and the design of a one-dimensional rough metal surface that produces an enhanced backscattering peak for only a single, specified, angle of incidence, but does not give rise to a specular peak. We have also shown new features of angular intensity correlation function $C^{(10)}$ and high order speckle correlations from rough surface scattering.

Although there has been much work done in correlation-induced spectral changes, a significant contribution has been accomplished from rough surface scattering for large changes in the spectrum of light from a rough dielectric film on a metal substrate. For spectral coherence, we have shown the spectral redistribution from moving ground glass with double passage configuration and the interference of a Collett-Wolf source.

For the temporal coherence from rough surface scattering, interference of 1-D and 2-D symmetrical Collett-Wolf beams is displayed, and we have shown the Young's interference pattern formed with symmetrical partially coherent sources. We have also found a method for the detection of the temporal coherence from partial coherence sources.

In addition, pseudo non-diffraction beams and influence of rough walls for random lasers have been studied. The principal goal of this study is to increase our theoretical understanding of localization, coherence and fluctuation from rough surface scattering. Concurrently, the results should have many potential applications in new material, devices and sensors for remote sensing, optical tag, nano-fabrication, and telecommunication.

2.0 SUMMARY OF PREVIOUS RESEARCH

In this section we shall summarize our past research main achievements during the period 1 July 2002 through 31 October 2005. Through Grant DAAD19-02-C-0056, a total of 18 papers were published that are listed in Section 3.0.

2.1 Spatial Coherence from Rough Surface Scattering

- **Enhanced Backscattering at Grazing Angle**

Backscattering signals at small grazing angles are very important for vehicle re-entrance and subsurface radar sensing applications. They are also useful in FTIR grazing angle microscopy. Recently,

we performed an experimental study of far-field scattering at small grazing angles, in particular, enhanced backscattering at grazing angles. For a randomly weak rough dielectric film on a reflecting metal substrate, a much larger enhanced backscattering peak is measured. Experimental results are compared with small perturbation theoretical predictions.[1]

The mechanism responses may be due to Quetelet's rings; the energy of diffusion is redistributed and a large portion of energy is attracted to the retro-reflection direction at the grazing angle. This explains why a large backscattering peak appears on the grazing angle.

- **New Features of Angular Intensity Correlation Function $C^{(10)}$ from Rough Surface Scattering**

The memory effect and the time-reversed memory effect in the angular intensity correlation function of p-polarized light scattered from a dielectric film (photoresist) deposited on a glass substrate have been investigated experimentally.[2] The vacuum-dielectric interface is a one-dimensional randomly rough interface, while the dielectric-glass interface is planar. A CCD camera was used to record the speckle pattern in the specular direction for each angle of incidence, and the angular intensity correlation function was then calculated from the digitalized images. The resulting correlation function displayed two well-defined peaks, one of which was the memory effect peak, and the other of which was the reciprocal memory effect peak. These peaks contain much the same information as the enhanced backscattering peak. However, their observation is much simpler because they can occur far from the retroreflection direction.

The memory effect has also been observed experimentally in the angular intensity correlation function of light scattered in its double passage through a random phase screen.[3] The theory of this effect had been worked out by H. Escamilla, E.R. Méndez and D. Hotz.[4] The manner in which the speckle pattern is predicted to move as the source is moved and the symmetry of speckles around the backscattering direction are verified experimentally.

An additional short-range correlation $C^{(10)}$ has also been investigated experimentally[5], which shows the symmetry of the speckle pattern around the specular direction in the far-field scattering from a rough surface.

The function $C^{(10)}$ has been overlooked in earlier studies due to the use of the factorization approximation, which presents a new type of memory effect, and its magnitude is comparable with that of $C^{(1)}$. $C^{(10)}$ can be observed if the following is satisfied:

$$\sin\theta_{i1} + \sin\theta_{i2} = \sin\theta_{s1} + \sin\theta_{s2} \qquad \textbf{(2.1-1)}$$

1 Zu-Han Gu, I.M. Fuks, and Mikael Ciftan, "New Features of Scattering from a Dielectric Film on a Reflecting Metal Substrate (Part I)," A chapter in the Book Wave Propagation, Scattering and Emission in Complex Media, 281-29, (World Scientific, 2004)).
2 J.Q. Lu and Zu-Han Gu, Appl. Opt. **36**, 4562-4570 (1997).
3 Z.Q. Lin and Zu-Han Gu, Appl. Opt. **39**, 4684-4689 (2000).
4 H. Escamilla, E.R. Méndez and D. Hotz, Appl. Opt. 32, 2734 (1993).
5 Zu-Han Gu, J.Q. Lu, and M. Ciftan, a chapter in the book Frontiers of Laser Physics and Quantum Optics, 201-203, Springer (2002).

If we set θ_{i1} is equal to θ_{i2}, and θ_{s1} is equal to $\theta_{i1} + \Delta\theta$, then θ_{s2} should be $\theta_{i1} - \Delta\theta$ which locates on the other side of the specular direction $(-\theta_{i1})$ and is symmetrical to θ_{s1} around the specular direction. The experimental results were presented to verify the validity of the theoretical analysis. For a two-dimensional photoresist film on the glass substrate, the incident laser is He-Ne with wavelength at 0.6328 microns, the incident angle θ_{i1} is 20° and the scattering angle θ_{s1} is -10°. The surface profile of the sample was measured with the standard deviation of heights σ is approximately 110Å and the 1/*e* value of the correlation length is approximately 2800Å.

The specular direction is at θ_{s2} = 20°, you can find the correlation function $C^{(10)}$ is symmetrical around the specular direction. Since the far-field low-order scattered amplitude is proportional to the Fourier transform of the real surface profile, which is Hermitian function, therefore the far-field scattered intensity should be symmetrical with respect to the specular direction. The low-order angular correlation function $C^{(10)}$ is proportional to the correlation of the scattered intensity, therefore $C^{(10)}$ is symmetrical around the speckle direction.

Although the angular intensity correlation functions calculated from the scattering of light from 1-D and 2-D random metal surfaces display the $C^{(1)}$, $C^{(10)}$, $C^{(1.5)}$, $C^{(2)}$, and $C^{(3)}$ correlations,[6] the $C^{(1.5)}$, $C^{(2)}$, and $C^{(3)}$ correlation functions need be further measured.

- **<u>High Order Speckle Correlation from Rough Surface Scattering</u>**

In the multiple scattering regime, there are similarities between Universal Conductance Fluctuations in mesoscopic conductors and rough surface scattering. There are three types of correlations: the short-range or the low order correlation, the long-range and the infinite-range, or the high order correlations.

The angular high order correlation function of speckle patterns scattered from a rough surface has been studied experimentally. Two experiments were set up with a fabricated 1-D random rough dielectric film on glass substrate and a randomly weak rough dielectric film on a reflecting metal substrate. The angular amplitude and intensity correlation functions are defined and measurements were carried out with the monostatic bidirectional reflectometer. The intensity-intensity correlation contains $C^{(1)} + C^{(2)} + C^{(3)}$, and the amplitude-amplitude correlation holds only the pure memory effect $C^{(1)}$. When the input laser beam size is comparatively small or close to the travel pass length inside the film, $C^{(2)}$ and $C^{(3)}$ are measured by subtracting amplitude-amplitude correlation from intensity-intensity correlation.[7]

While in rough surface scattering it has been shown that a strong angular memory effect $C^{(1)}$ can be observed if the following conditions are satisfied:

$$\sin\theta_{i1} - \sin\theta_{s1} = \sin\theta_{i2} - \sin\theta_{s2} \quad . \qquad \textbf{(2.1-2)}$$

A correlation $C^{(1)}$ exists as long as this quantity is not violated by more than λ/*W*, where *W* is the illuminated width of the surface and λ is the wavelength. $C^{(1)}$ drops to zero exponentially with the increase of $\Delta\theta$, whereas $C^{(2)}$ and $C^{(3)}$ are much smaller than $C^{(1)}$. However, $C^{(2)}$ and $C^{(3)}$ decay slowly;

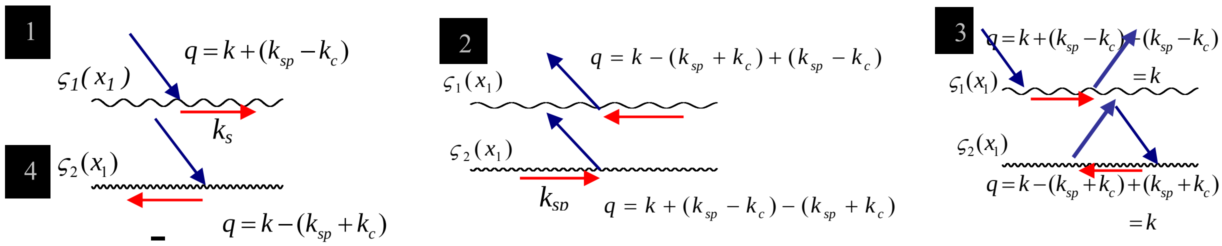
6 V. Malyshkin, A.R. McGurn, T.A. Leskova, A.A. Maradudin, and M. Nieto-Vesperinas, Waves in Random Media **7**, 479-520 (1997).
7 Zu-Han Gu, "High Order Correlations from Rough Surface Scattering," Applied Optics **43**, No. 15, 3061-3065 (2004).

they are nonzero for a much larger range of incident angle change. In this case, the intensity correlation function C only remains the high order correlation $C^{(2)}$ and $C^{(3)}$.

- **<u>Design of a One-Dimensional Rough Metal Surface that Produces an Enhanced Backscattering Peak for only a Single, Specified, Angle of Incidence, but does not give rise to a specular peak</u>**

The enhanced backscattering of light from a randomly rough surface is the presence of a well-defined peak in the retroreflection direction in the angular dependence of the intensity of the light scattered from the surface, for any angle of incidence. In a recent publication[8] it was shown how to design a one-dimensional randomly rough metal surface that produces an enhanced backscattering peak for only a single, specified angle of incidence, when it is illuminated by p-polarized light. However, this peak was accompanied by a peak in the specular direction of a comparable magnitude. During this period we have developed a different approach to the design of a one dimensional rough metal surface that produces an enhanced backscattering peak for only a single, specified angle of incidence, but does not give rise to a specular peak. It is based on representing the surface profile function as a sum of two periodic profiles with different periods $\varsigma(x_1) = s_1(x_1) + s_2(x_2)$, where $s_1(x_1 + a_1) = s_1(x_1)$ and $s_2(x_1 + a_2) = s_2(x_1)$. The periods of the two gratings are chosen to produce a resonant excitation of forward and backward propagating surface plasmon polaritons supported by the metal-vacuum interface by the light incident at the specified angle of incidence θ_c. Thus, $a_1 = \lambda / (\sin\theta_c + n_{sp}(\lambda))$, where $n_{sp} = Re\sqrt{\varepsilon(\omega)/(1+\varepsilon(\omega))}$ is the refractive index of surface plasmon polaritons, and the grating of this period effectively excites forward propagating surface waves. The second grating has a period $a_2 = \lambda / (\sin\theta_c - n_{sp}(\lambda))$, and effectively excites backward propagating surface plasmon polaritons. Furthermore, the forward propagating surface plasmon polaritons interact with the grating of the period a_2 and are converted back into volume waves in the vacuum that are radiated in the retroreflection direction. Analogously, the backward propagating surface plasmon polaritons interact with the grating of the period a_1 and are converted back into volume waves in the vacuum that are also radiated in the retroreflection direction. These waves interfere constructively to produce the enhanced backscattering peak. Such a surface was fabricated by West and O'Donnell[9], and was shown to display the enhanced backscattering peak. A strong specular peak is also present in the intensity of the scattered light. However, our work shows that a careful choice of the amplitudes of the two gratings can lead to a further enhancement of the peak in the backscattering direction and a complete elimination of the specular peak (see Figure 2.1-1 and 2.1-2).

[8] SPIE **4447**, 17-23 (2001).
[9] Optics Communications, **123**, 109-114 (1996).



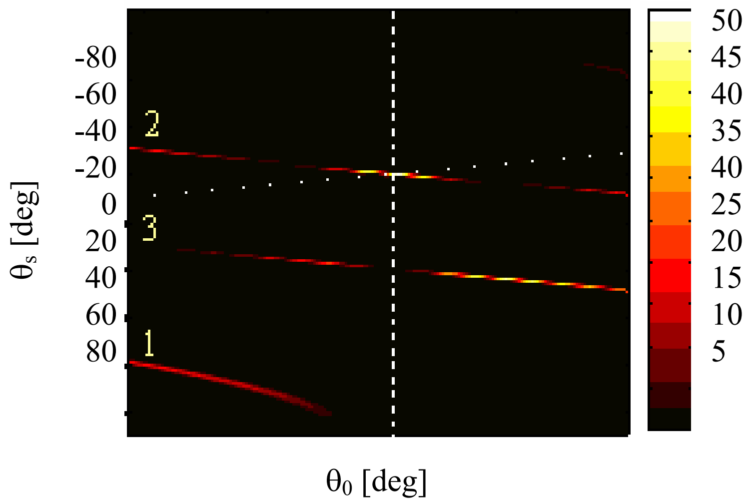


***Figure 2.1-1*: A color-level plot of the scattered intensity as a function of the angles of incidence and scattering. The dotted line shows the backscattering direction, the vertical dashed line shows the prescribed angle of incidence at which all the incident light power is scattered back, $\theta_0 = \theta_c = 20^\circ$.**

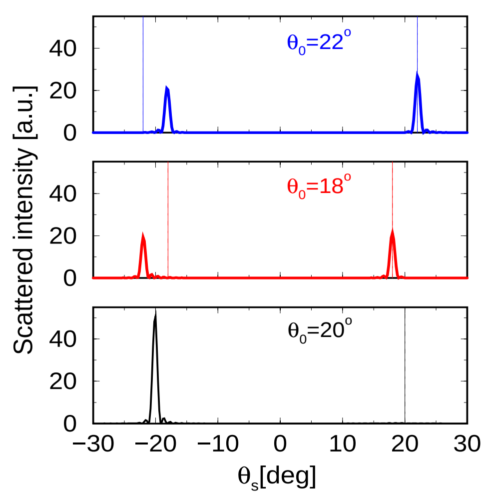


***Figure 2.1-2*: Plots of the scattered intensity as a function of the angle of scattering for three angles of incidence θ_0 = 20°, 18°, and 22°. The vertical dashed lines show the backscattering and specular directions, θ_s = ±18° (red) and θ_s = ±22° (blue).**

2.2 Spectral Coherence from Rough Surface Scattering

- **Spectral Redistribution from Moving Ground Glass with Double Passage Configuration**

Changes in the spectrum of light scattered by a moving diffuser plate were investigated theoretically and experimentally. A theoretical expression showed the changes of the spectrum due to both the motion of the diffuser plate and the statistical properties of the plate. A multi-mode laser was used to test the spectral changes. However, the frequency shifts were small. We have studied another approach to investigate by means of double passage configuration.

The folded path or double passage scattering configuration is known to exhibit enhanced backscattering with a sharp backscattering peak, similar in size to that of the speckle produced in the far-field of the diffuser-mirror combination. It is also known that when the system is illuminated by a point source, a well-defined intensity peak, centered on the conjugate point to that of the point source, is present in the scattered light. In other words, the random structure appears to focus, at least partly, the scattered light on this spot. This peak plays the role of the point spread function of an imaging system.

The results presented in this work demonstrate the changes in spectrum of light scattered from the double passage configuration. We have set up a double passage configuration with moving ground glass of a two-dimensional randomly rough surface, which is known to exhibit an enhanced backscattering peak. A low resolution real image is centered on the conjugate point to that of the point source. A blue shift is measured at the center of the real image as well as the red shift at the edge of the image.[10]

The mechanism responsible for the spectral shifts may be due to multiple scattering where the enhanced backscattering peak can be considered as having been radiated by a planar secondary source. In this case, the spectral degree of coherence, or the complex degree of spectral coherence, does not satisfy the scaling law and consequently the spectrum of light at the real image of the point source is redistributed.

- **Large Changes in the Spectrum of Light from a Rough Dielectric Film on a Metal Substrate**

Theoretical calculations have shown that in order to obtain changes in the spectrum of light scattered from a randomly rough surface that are large enough to be observed experimentally, this spectrum should be measured at angles of scattering in the near vicinity of features in the scattering pattern whose angular positions depend strongly on the frequency of the incident light. A scattering system that possesses such features is a dielectric film deposited on the planar surface of a reflecting substrate whose illuminated surface is a two-dimensional randomly rough surface. When the dielectric surface is weakly rough, coherent light scattered from this system consists of speckle spots that arrange themselves into concentric interference rings, called Selényi rings, centered at the normal to the mean surface. The angular positions of these rings (intensity maxima) are independent of the angle of incidence of the incident light.

When the dielectric surface is strongly rough the angular positions of these rings now depend on the angle of incidence, and they are called Quételet rings. The angular positions of both types of rings

[10] Zu-Han Gu, "Changes in Spectrum of Light Scattered from Double Passage Configuration," SPIE **4780**, 24-31 (2002)

depend strongly on the wavelength of the incident light. Therefore, the spectrum of the scattered light, measured at a scattering angle close to the position of one of these rings, can differ significantly from that of the incident light. We study experimentally the scattering of light from the system just described, namely a dielectric film deposited on the planar surface of a metallic substrate, when the illuminated surface of the film is a two-dimensional randomly rough surface. We find large changes in the spectrum of the scattered light at scattering angles in the neighborhood of the fringes in the scattering pattern to which this system gives rise. This expectation is confirmed by our numerical simulation seeing Figures 2.2-1 and 2.2-2.[11]

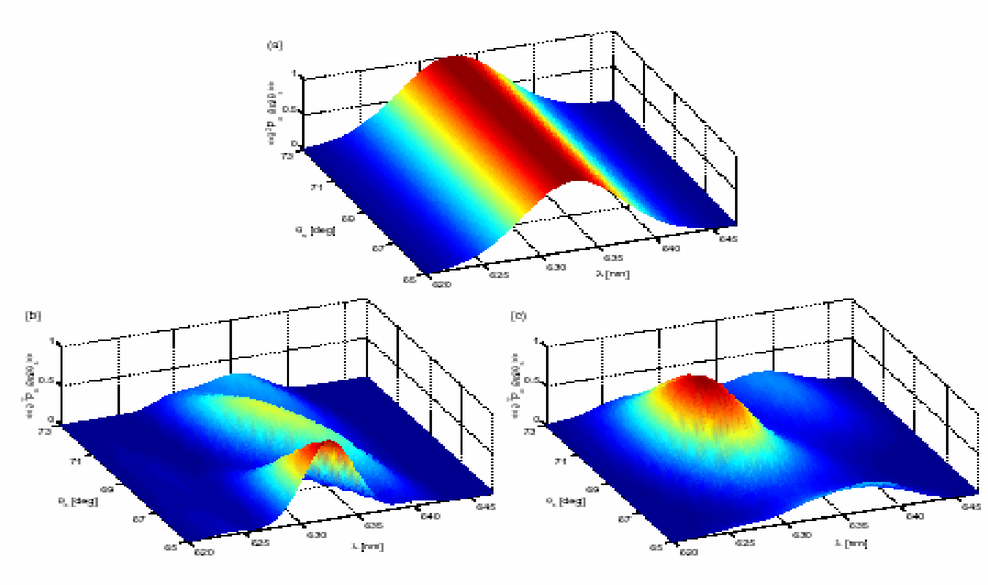


***Figure 2.2-1*: The spectral density of the light scattered into directions around $\theta_s = 69°$; (a) in the absence of the roughness induced correlations, (b) a weakly rough surface with a single-scale roughness, and (c) a strongly rough surface with a two-scale roughness. The angle of incidence $\theta_0 = 40°$.**

[11] Zu-Han Gu, Tamara A. Leskova, Alexei A. Maradudin, and Mikael Ciftan, "A Wolf Effect in Rough Surface Scattering," A Chapter in the book **Tribute to Emil Wolf**, 223-245 (SPIE press, 2004).

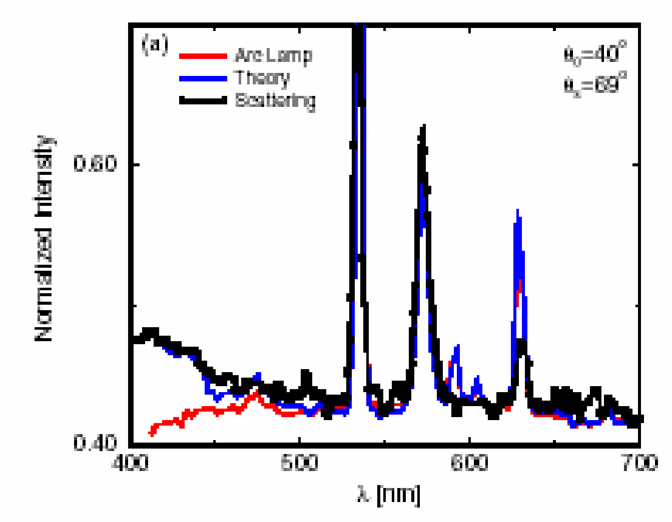
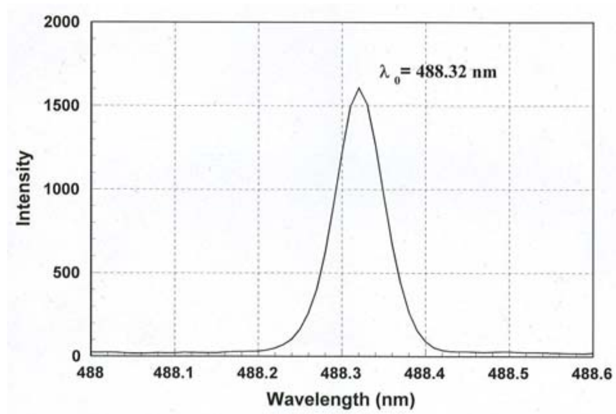


Figure 2.2-2**: The wavelength dependence of the differential intensity of the light scattered into the directions $\theta_s = 69°$. The angle of incidence $\theta_0 = 40°$. The red curves give the intensity of the incident light (Arc Lamp), the black rectangles give the measured intensity of the scattered light, and the blue curves are the calculated wavelength dependences of the scattered light in the case where the spectral density $S_0(\omega)$ is obtained from the spectrum of the incident light.**

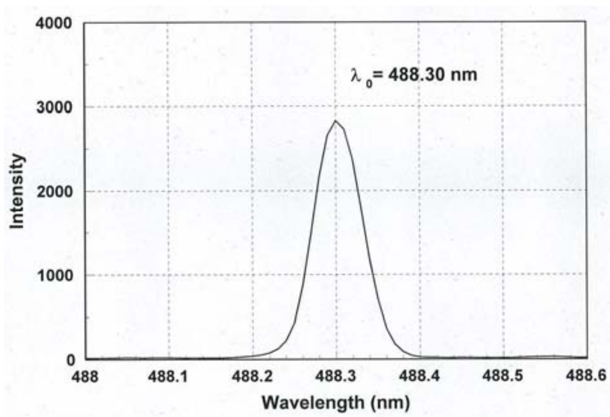
- **Spectral Redistribution from the Interference of a Collett-Wolf Source**

By applying a Mach-Zehnder interferometer to a pair of symmetrical Collett-Wolf sources, the temporal average over an ensemble of realizations of the output power spectrum of the interferometer will display a bright coherent line, which shows the temporal coherence behavior of the input beam. Recently we have further studied the spectral coherence from the interference of a Collett-Wolf source and found a large change in the spectrum of the light.

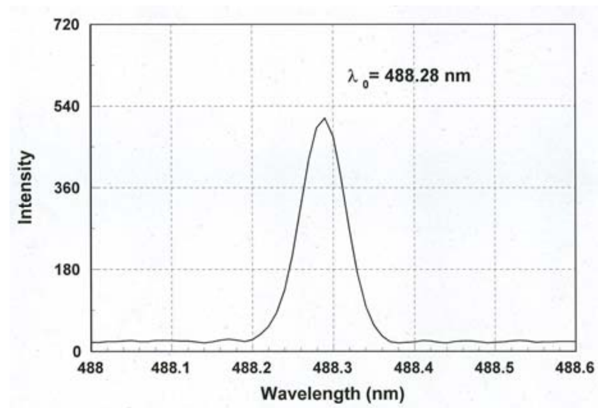
Experimental results are shown in Figures 2.2-3 and 2.2-4. Figure 2.2-3 (a) is the spectrum of an Argon Ion laser, 2.2-3 (b), the spectral redistribution from the Collett-Wolf source with Ar laser, and 2.2-3 (c), the spectral redistribution from the interference of a Collett-Wolf source. The peak of the interference source is blue-shifted with 0.04 nm. We have also made a measurement for the spectrum redistribution from the interference of a Collett-Wolf source with a Tungsten lamp. The peak of the interference source is blue-shifted with 21.5 nm (see Figure 2.2-4).



(a) Spectrum of Ar Laser

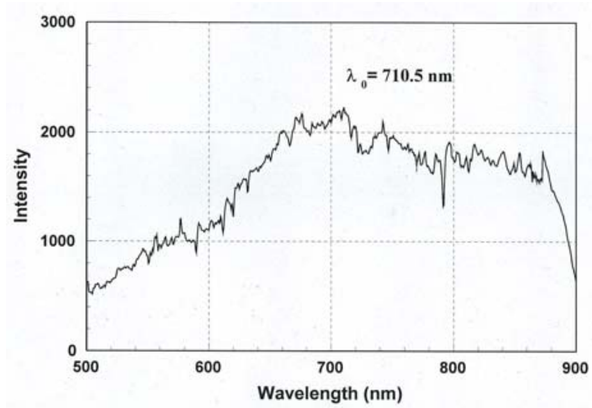


(b) Collett-Wolf Source with Ar Laser.

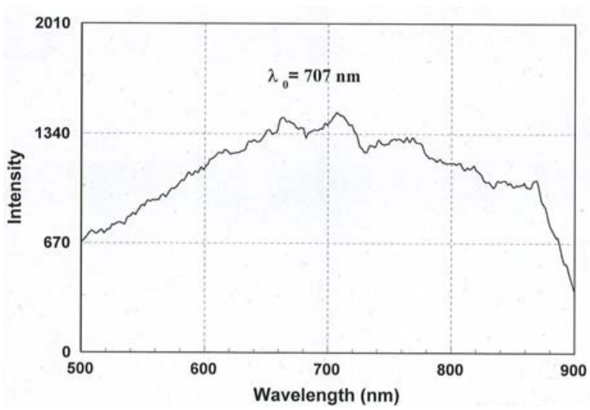


(c) Interference of a Pair of Collett-Wolf Source.

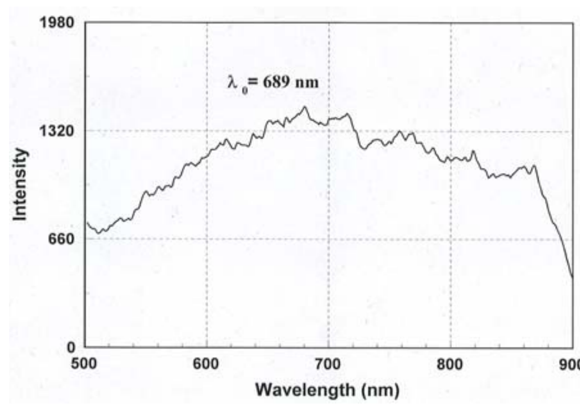
***Figure 2.2-3*: The spectrum of the output of the interference of a Collett-Wolf source with Argon Ion Laser.**



(a) Spectrum of Tungsten Lamp.



(b) Spectrum of Tungsten Lamp with Collett-Wolf Source.



(c) Interference of a Pair of Collett-Wolf Source.

***Figure 2.2-4*: The spectrum of the output of the interference of a Collett-Wolf source with Tungsten Lamp.**

The mechanism responsible for the spectral shifts may be due to multiple scattering where the diffused transmission can be considered as having been radiated by a planar secondary source. In this case, the spectral degree of coherence or the complex degree of spectral coherence does not satisfy the scaling law and consequently the spectrum of light is redistributed.

2.3 Temporal Coherence from Rough Surface Scattering

- **Interference of 1-D and 2-D Symmetrical Collett-Wolf Sources**

Collett-Wolf source, which can be obtained by means of suitable moving 2-D random rough surface or ground glass, can produce a field as directional as a laser beam, although from a global viewpoint the source is nearly spatially incoherent. Such a source with unique features of no speckle noise has been widely used for imaging and illuminations. Recently, we have repeated Gory's setup by designing a Gaussian aperture filter, and we have also measured σ_S and σ_g.

We have measured the interference of 1-D and 2-D symmetrical Collett-Wolf sources with a new setup which is a modified Michelson interferometer (see Figure 2.3-1). Figure 2.3-2 shows the images of interference with (a) a pair of symmetrical Collett-Wolf sources, and (b) a pair of asymmetrical Collett-Wolf sources.

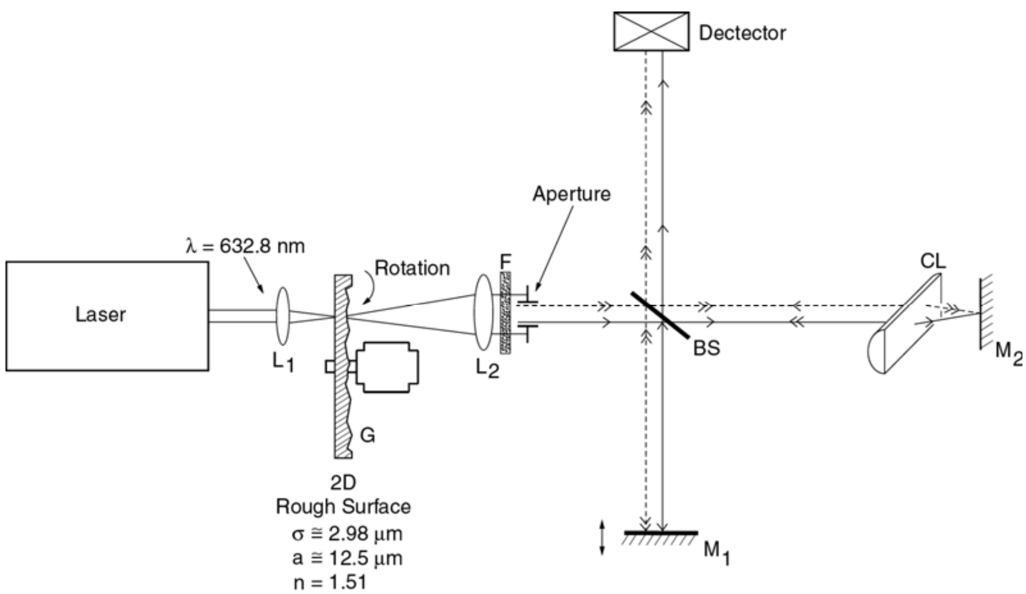
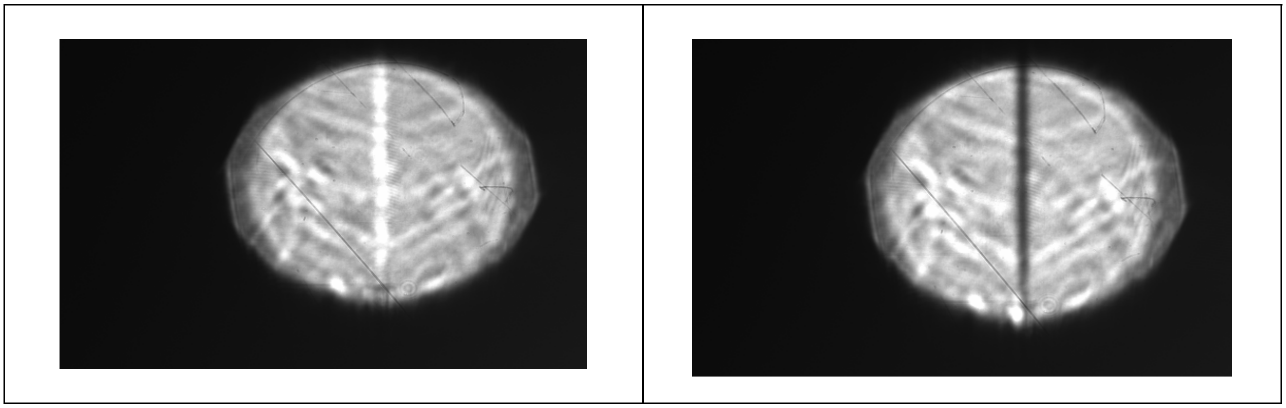


***Figure 2.3-1*: A Modified Michelson Interferometer for 1-D Symmetrical Collett-Wolf Source.**



(a) *(b)*

***Figure 2.3-2*: The Images of the Interference with (a) and (b).**

- **<u>Young's Interference Pattern Formed with Symmetrical Partially Coherent Sources</u>**

It has been shown not long ago by Emil Wolf, the Young's interference pattern is formed by partially coherent light. The coherent properties of interfering beams from two pinholes after they passed through a moving diffuser are determined by the correlation function of the heights of the diffuser surface and speed with which the diffuser is moving (see Figure 2.3-3).

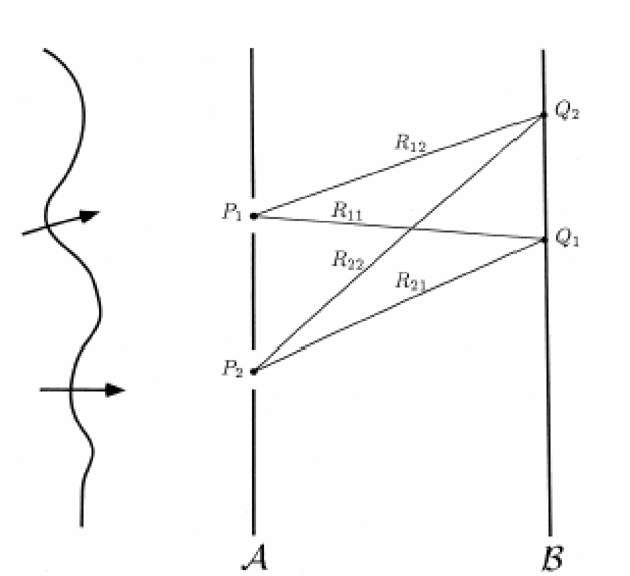
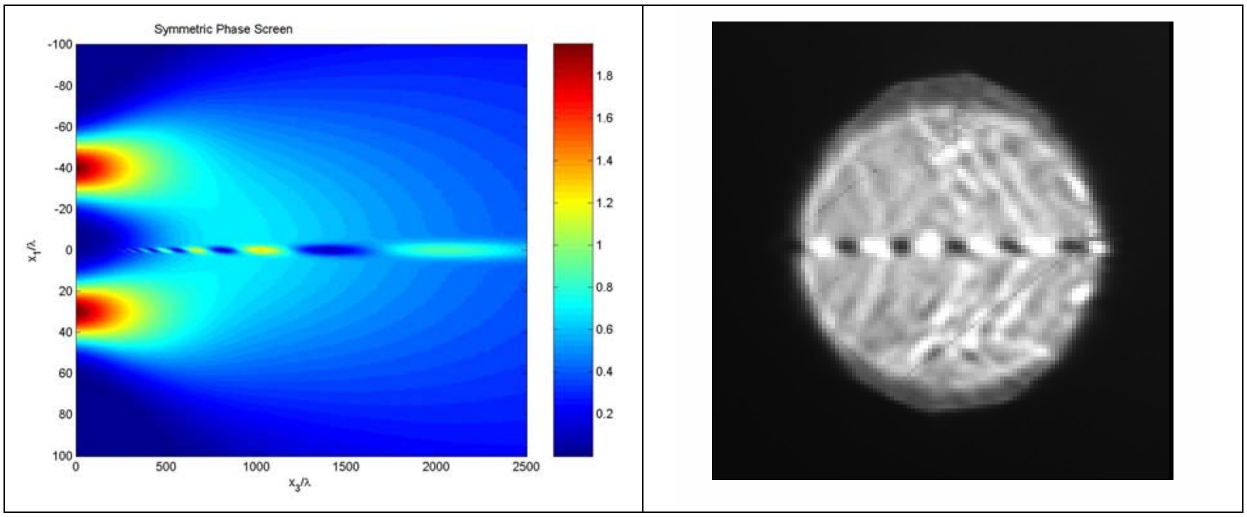


***Figure 2.3-3*: Yang' s interference pattern formed with partially coherent light. (After S A. Ponomarenko, E. Wolf, Opt. Comm., 170, 1999.)**

Combining the Young's (spatial) and Michelson (temporal) interference, we have a setup of the modified Mach-Zehnder stellar interferometer to implement the Yang's interference for a pair of symmetrical Collett-Wolf beams. The collimated laser beam with the wavelength λ = 632.8 nm is incident through a 2-D rough surface acting as a ground glass. M_3 mirror is used to generate a symmetrical Collett-Wolf source. Behind the two slits S_1 and S_2, a lens L_3 is set for the stellar interferometer. It is found that regardless of the spectral degree of coherence of the source, the maximal fringe patterns appear at all pairs located symmetrically with respect to the optical axis.

We have also played the rigorous computer simulations for the stellar interference of the partially coherent source. Thus we show theoretically and experimentally that the stellar interference of the radiation from a pair of Collett-Wolf sources exhibits the high-order fringes that can be used to determine the temporal and spectral degree of coherence of the partially coherent light source (see Figure 2.3-4).



(a) (*b*)

Figure 2.3-4**: (a) The Numerical Calculation, and (b) the Experimental Results of Young's Interference Pattern Formed with Symmetric Partially Coherent Sources.**

- <u>**Detection for the Temporal Coherence from Partial Coherence Source**</u>

Collett-Wolf source, which can be obtained by means of suitable moving phase screens or ground glass, can produce a field as directional as a laser beam, although from a global viewpoint the source is nearly spatial incoherent. Such a source with unique features of no speckle noise has been widely used for imaging, illumination, and pointing for many years. However, further study of such a source is needed for the advanced detection of temporal coherence from specially uncorrelated speckles.

Experimentally, one way we have investigated is to apply speckle interferometry to a Collett-Wolf source. The experimental setup is a Mach-Zehnder interferometer. A 2-D random rough surface is used for the diffuser and rotation of the random surface is needed to generate Collett-Wolf source. To create symmetry of the input beam, a mirror M_3 is inserted in one of the arms. Since the coherent effects in the scattering of light from random surfaces with symmetry can generate a diffuse specular component in the reflection and transmission, and if we have a similar setup with a center of symmetry, the temporal

ensemble of realizations of the output power spectrum of a Mach-Zehnder interferometer will have a bright coherent line in the center which shows the temporal coherent nature of the input beam. Figure 2.3-5 shows the design of a new instrument for the measurement of temporal coherence of the Collett-Wolf source.[12]

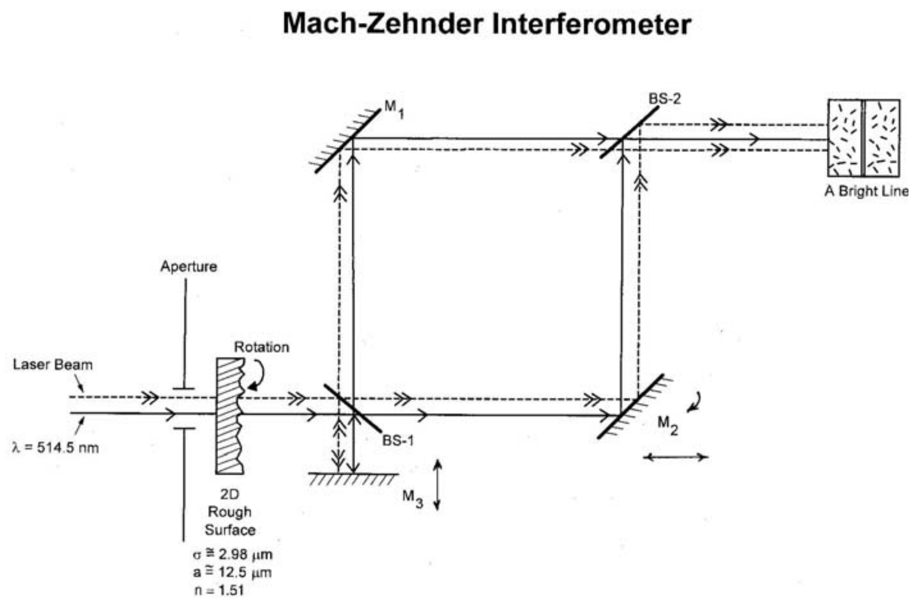


***Figure 2.3-5*: Detection of the Temporal Coherence.**

2.4 Pseudo Non-diffraction Beam

We have the experimental results displaying the interference of light produced by a pair of Collett-Wolf sources. By applying Mach-Zehnder interferometer to a pair of symmetrical Collett-Wolf sources, the temporal average over an ensemble of realizations of the output power spectrum of the interferometer will display a narrow bright coherent line at the center, which shows the temporal coherence behavior of the input beam. These sources are either symmetric or antisymmetric with respect to a plane midway between them. In the former case the output radiation from the interferometer in the far-field is a beam with an intensity distribution that displays a narrow bright line at its center that diverges with the distance from the sources much more slowly than the beam itself. In the later case the radiated beam has an intensity distribution with a narrow dark line at its center. We illustrate this in Figures 2.4-1 (a) and (b). These results suggest that the interference of a pair of symmetric Collett-Wolf beams can be used to produce a pseudo-nondiffracting beam. The experimental results are supported by the results of theoretical calculations.[13]

12 Zu-Han Gu, "Interference with a Collett-Wolf Source", SPIE **5189**, 128-133 (2003).

13 Zu-Han Gu, M. Ciftan, A.A. Maradudin and T.A. Leskova, "Interference of a Pair of Symmetric Collett-Wolf Beams", Opt. Lett., Vol. 30, No. **13**, 1605-1607 (July 2005).

For the parameters of the Collett-Wolf source we used in our calculations the angular divergence of the beams is ≅ 0.5 mrad, while the angular divergence of the interference line is ≅ 0.02 mrad. The measurements of the angular divergence of the interference line shows 0.05 mrad.

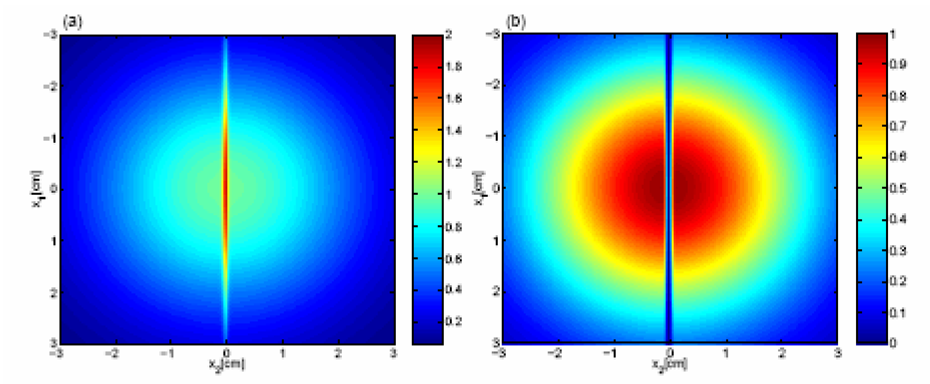


***Figure 2.4-1*: A color-level plot of the cross-section of the normalized intensity of the symmetric (a) and antisymmetric (b) beams. The distance from the source plane is x_3 = 1 m, σ_s = 2.54 cm, σ_g = 1 mm, and λ = 514.5 nm.**

2.5 High Order Correlation from Moving Surface

We have applied an optical setup of a randomly weak rough dielectric film on a reflecting metal substrate for the measurement of high order correlations from rough surface scattering. The angular amplitude and intensity correlations are measured. Due to multiple-scattering, when the input laser beam size is comparatively small or close to the travel pass length inside the film, $C^{(2)}$ and $C^{(3)}$ are measured by subtracting amplitude correlation from intensity correlation.

We have also studied the scattering of light from a moving randomly rough surface. In this first study we assume that the interface between the vacuum and the scattering medium is moving parallel to itself with a constant speed V in a direction perpendicular to the generators of the surface. The equation of the surface then can be written as $x_3 = \zeta(x_1 - Vt)$, where the surface profile function $\zeta(x_1)$ is a single-valued function of x_1, that is differentiable as many times as is necessary, and constitutes a stationary, zero-mean Gaussian random process defined by

$$<\zeta(x_1)\zeta(x_1^{'})> = \delta^2 \exp[-|\mathrm{x}_1 - x_1^{'}|/a^2]\,. \qquad (2.5\text{-}1)$$

The angle brackets in Eq. (2.5-4) denote an average over the ensemble of realizations of $\zeta(x_1)$, and $\delta = <\zeta^2(x_1)>^{1/2}$ is the rms height of the surface.

The random surface is illuminated from the vacuum side by a p-polarized electromagnetic field of frequency ω whose plane of incidence is the x_1x_3-plane. The single nonzero component of the magnetic field in the vacuum region is the sum of an incident wave and of scattered waves,

$$H^{>}(x_1,x_3\,|\,t) = \exp\left[\mathrm{i}(\mathrm{kx}_1 - \alpha_0(k,\omega)x_3 - \omega t)\right] + \int_{-\infty}^{\infty}\frac{d\Omega}{2\pi}\int_{-\infty}^{\infty}\frac{dq}{2\pi}R(q\,|\,k)\exp\left[\mathrm{i}(\mathrm{qx}_1 + \alpha_0(q,\Omega)x_3 - \Omega t)\right], \tag{2.5-2}$$

where

$$\alpha_0(q,\Omega) = \sqrt{(\Omega/c)^2 - q^2}\ , \quad \mathrm{Re}\,\alpha_0(q,\Omega) > 0\ , \quad \mathrm{Im}\,\alpha_0(q,\Omega) > 0\ , \tag{2.5-3}$$

The reduced Rayleigh equation for the scattering amplitude $R(q\,|\,k)$ has the form:

$$\int_{-\infty}^{\infty}\frac{d\Omega'}{2\pi}\int_{-\infty}^{\infty}\frac{dq}{2\pi}M(q,p\,|\,\Omega')2\pi\delta(\Omega-\Omega'-(p-q)V)R(q\,|\,k) = -N(p,k\,|\,\omega)2\pi\delta(\Omega-\omega-(p-k)V)\ , \tag{2.5-4}$$

where

$$M(p,q\,|\,\Omega) = \frac{pq + \alpha(p,\Omega)\alpha_0(q,\Omega)}{\alpha(p,\Omega) - \alpha_0(q,\Omega)}I(\alpha(p,\Omega) - \alpha_0(q,\Omega)\,|\,p-q)\ , \tag{2.5-5}$$

$$N(p,q\,|\,\Omega) = \frac{pq - \alpha(p,\Omega)\alpha_0(q,\Omega)}{\alpha(p,\Omega) + \alpha_0(q,\Omega)}I(\alpha(p,\Omega) + \alpha_0(q,\Omega)\,|\,p-q)\ , \tag{2.5-6}$$

where

$$\alpha(q,\Omega) = \sqrt{\varepsilon(\Omega)(\Omega/c)^2 - q^2}\ , \quad \mathrm{Re}\,\alpha(q,\Omega) > 0\ , \quad \mathrm{Im}\,\alpha(q,\Omega) > 0\ , \tag{2.5-7}$$

and

$$I(\gamma\,|\,Q) = \int_{-\infty}^{\infty}dx_1 e^{-iQx_1}e^{-i\gamma\zeta(x_1)}\ . \tag{2.5-8}$$

The replacement

$$R(q\,|\,k) = \widetilde{R}(q\,|\,k)2\pi\delta(\Omega-\omega-(q-k)V) \tag{2.5-9}$$

in Eq. (2.5-4) transforms it into

$$\int_{-\infty}^{\infty}\frac{dq}{2\pi}M(q,p\,|\,\omega+V(q-k))\widetilde{R}(q\,|\,k) = -N(p,k\,|\,\omega)\ , \tag{2.5-10}$$

We seek the solution of this equation as an expansion in powers of the surface profile function to third order with the result in Figure 2.5-1 that the motion of the surface shifts the angular position of the enhanced backscattering peak away from the retroreflection direction. From the magnitude and sign of this shift it is possible to obtain the speed *V* of the moving surface.

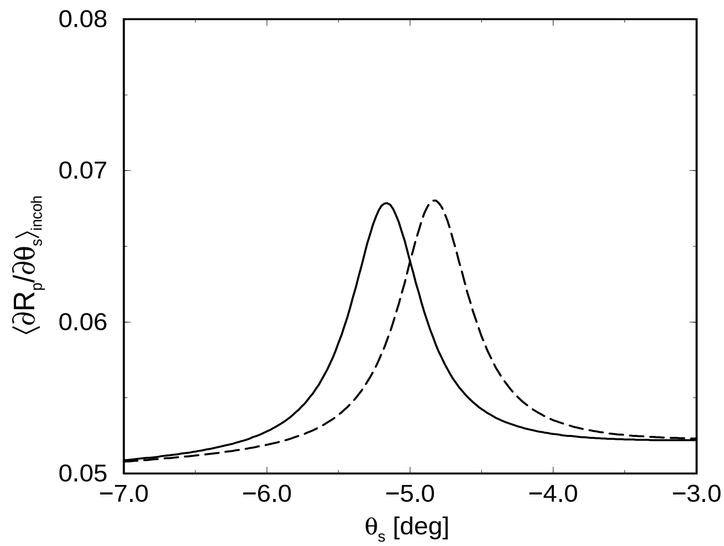


***Figure 2.5-1*: The mean differential reflection coefficient $<\partial R/\partial\theta_s>$ for the scattering of p-polarized light of wavelength $\lambda = 260$ nm from a one-dimensional random silver surface that is moving in the x_1-direction with a constant speed V=2×10^{-5} c (solid line) and *V*=-2×10^{-5} c (dashed line). The dielectric function of the metal at this wavelength is $\varepsilon(\omega) = -1.74 + i0.005$, and the angle of incidence is $\theta_0 = 5^\circ$. The rms height of the surface is $\delta = 5$ nm, and the transverse correlation length of the surface roughness is $a = 100$ nm.**

2.6 Influence of Rough Walls for Random Laser

A laser consists essentially of two parts: a gain medium that amplifies light and a feedback mechanism that temporarily traps the light in order for the amplification to be efficient. In conventional lasers this feedback is generally provided by two semitransparent planar mirrors. In recent work an alternative mechanism for providing the feedback required for lasing to occur has been actively investigated, namely, multiple scattering of light by randomness in the gain medium. Such scattering produces feedback through the mechanism of coherent enhanced backscattering, which manifests itself by the presence of a well-defined cone-shaped peak in the backscattering direction in the angular dependence of the intensity of the scattered light.

By the use of the finite-difference time domain (FDTD) method, we have calculated the electromagnetic field inside a two-dimensional waveguide system that is bounded by perfectly conducting walls. Part of the waveguide is filled with an active, isotropic, homogeneous medium whose amplifying properties resulting from stimulated emission processes are modeled by introducing a frequency-dependent conductivity into Maxwell's equations. The feedback provided by the reflections from the

walls of the waveguide and the interfaces between the active part and the adjacent vacuum leads to lasing for a sufficiently strong gain medium. Besides this conventional feedback, we use rough walls (see Figure 2.6-1) for the active part of the waveguide and investigate whether the scattering processes caused by these walls can enhance the confinement of the electromagnetic field and consequently lower the lasing threshold. In our numerical approach we trace the temporal evolution of the electromagnetic field and derive the energy flux and the intensity of the output to the vacuum regions adjacent to the gain medium. We also calculate the frequency spectrum of the emitted light, derive the lasing threshold of the laser, and finally, analyze all these characteristics for different choices of the roughness of the walls of the cavity.

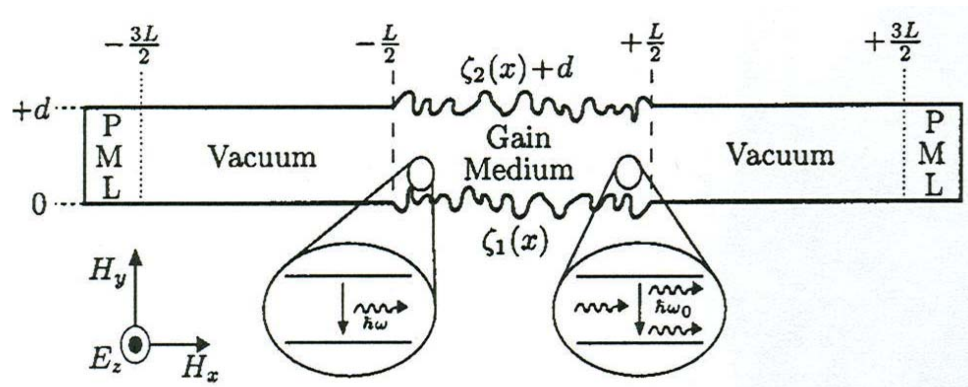


***Figure 2.6-1*: Layout of the two-dimensional waveguide system.**

We have calculated the electromagnetic field inside a two-dimensional waveguide system that is partly filled with an active medium and is bounded by perfectly conducting walls. We investigated the influence of rough walls of the laser cavity on the lasing threshold, the output intensity, and the frequency spectrum of the emitted light. The FDTD algorithm, on which our results are based, has successfully described key features of the lasing system, such as amplification of spontaneous emission, generation of waveguide modes as a manifestation of stimulated emission processes, and saturation effects in the active medium. For the system with two semitransparent mirrors that are due to an index step between the gain medium and the adjacent vacuum regions, we found that it is possible to lower the lasing threshold and increase the output intensity by employing an asymmetric sawtooth profile instead of planar walls.

3.0 LIST OF PUBLICATIONS

3.1 Papers Published under Support from Army Research Office Grant DAAD19-02-C-0056

1. Zu-Han Gu, I.M. Fuks, and M. Ciftan, “Enhanced Backscattering at Grazing Angles,” Optics Letters, Vol. 27, No. **23**, 2067-2069 (2002).

2. Zu-Han Gu, “Changes in Spectrum of Light Scattered from Double Passage Configuration,” SPIE **4780**, 24-31 (2002).

3. Zu-Han Gu, “High Order Correlation from Rough Surface Scattering,” SPIE **4780**, 15-23 (2002).

4. Zu-Han Gu, "Changes in the Spectrum of Light Scattered from a Rough Dielectric Film on a Metal Surface," SPIE **5189**, 45-49 (2003).

5. Zu-Han Gu, T.A. Leskova, A.A. Maradudin, and W. Thomson, "Comparison Between Theoretical Calculation and Measurement of Angular Spectrum Changes from Rough Surface Scattering," SPIE **5189**, 80-87 (2003).

6. Zu-Han Gu, "Angular Spectrum Redistribution from Rough Surface Scattering," a Chapter in the book Recent Research Development Optics, 107-123, Edited by S.G. Pandalai (Research Signpost, 2003).

7. Zu-Han Gu, "Interference with a Collett-Wolf Source," SPIE **5189**, 128-133 (2003).

8. Zu-Han Gu, Tamara A. Leskova, Alexei A. Maradudin, and Mikael Ciftan, "A Wolf Effect in Rough Surface Scattering," A Chapter in the book Tribute to Emil Wolf , 223-245 (SPIE press, 2004).

9. Zu-Han Gu, "High Order Correlations from Rough Surface Scattering," Applied Optics, Vol. 43, No. **15**, 3061-3065 (2004).

10. Zu-Han Gu, I.M. Fuks, and Mikael Ciftan, "Grazing Angle Enhanced Backscattering from a Dielectric Film on a Reflecting Metal Substrate," Optical Engineering, 43(**3**) 559-567 (March 2004).

11. Zu-Han Gu, I.M. Fuks, and Mikael Ciftan, "New Features of Scattering from a Dielectric Film on a Reflecting Metal Substrate (Part I)," A chapter in the Book Wave Propagation, Scattering and Emission in Complex Media, 281-293 (World Scientific, 2004).

12. M. Kretschmann and A.A. Maradudin, "Lasing Action in Waveguide Systems and the Influence of Rough Walls", J. Opt. Soc. Am. **B**, Vol. 21, 150-158 (2004).

13. Zu-Han Gu, M. Ciftan, A.A. Maradudin and T.A. Leskova, "Interference of a Pair of Symmetric Collett-Wolf Beams ", Optics Letters, Vol. 30, No. **13**, 1605-1607 (July, 2005).

14. Zu-Han Gu, "Spectral Redistribution from the Interference of a Collett-Wolf Source," SPIE **5878**, 0W1-6, (2005).

15. Zu-Han Gu, T.A. Leskova, A.A. Maradudin, and Mikael Ciftan, "Pseudo-nondiffraction from the Interference of a Collett-Wolf Source", SPIE **5878**, 101-107, (2005).

16. Zu-Han Gu, "Young's Interference Pattern Formed with Symmetrical Partially Coherent Sources," SPIE **5878**, 0X1-3, (2005).

17. Zu-Han Gu, T.A. Leskova, A.A. Maradudin, and W. Thomson, "Angular Spectrum Changes from 1-D Rough Surface Scattering," submitted to Optics Letters (2005).

18. A.A. Maradudin, E.R. Méndez, and T.A. Leskova, Zu-Han Gu, "One-dimensional Random Surfaces that Display Enhanced Backscattering for One Specified Angle of Incidence", submitted to J.O.S.A.B. (2005).

3.2 Invited Papers in Professional Conferences under Support from Army Research Office Grant DAAD19-02-C-0056

1. Zu-Han Gu, "High-order Correlation from Rough Surface Scattering", presented at SPIE Annual Meeting in Seattle (2002).

2. Zu-Han Gu, "Changes in Spectrum of Light Scattered from Double Passage Configuration", presented at SPIE Annual meeting in Seattle (2002).

3. Zu-Han Gu, "Angular Spectrum Redistribution from Rough Surface Scattering', presented at PIERS 2002 at Cambridge (2002).

4. Zu-Han Gu, "Change in the Spectrum of Light Scattered from a Rough Dielectric Film on a Metal Surface", presented at SPIE Annual meeting in San Diego (2003).

5. Zu-Han Gu, T.A. Leskova and A.A. Maradudin, "Comparison between Theoretical Calculations and Measurement of Angular Spectrum Changes from Rough Surface Scattering", presented at SPIE Annual meeting in San Diego (2003).

6. Zu-Han Gu, "Interference with a Collett-Wolf Source", presented at SPIE Annual meeting in San Diego (2003).

7. Zu-Han Gu, "Changes in Spectrum of Light Scattered from Double Passage Configuration", presented at PIERS 2003 in Singapore (2003).

8. Zu-Han Gu, "New Feature of Scattering from a Dielectric Film on a Reflecting Metal", presented at PIERS 2003 in Hawaii (2003).

9. Zu-Han Gu, "Spatial, Temporal and Spectral Coherence from Rough Surface Scattering", presented at ARO Workshop on "Multiple Scattering and Partial Coherence", at Costa Mesa, California (2003).

10. Zu-Han Gu, T.A. Leskova, A.A. Maradudin and M. Ciftan, "A Wolf Effect in Rough Surface Scattering", presented at Tribute to Emit Wolf Workshop at SPIE Annual meeting in San Diego (2003).

11. Zu-Han Gu, "Spectral Redistribution from the Interference of a Collett-Wolf Source", presented at ARO Workshop on "Variable Coherence", at Costa Mesa, California (2004).

12. T.A. Leskova, A.A. Maradudin, E.R. Méndez and Zu-Han Gu, "The Design of One-dimensional Randomly Rough Surface that act as Collett-Wolf Source", presented at PIERS 2004 in Nanjing, China (2004).

13. Zu-Han Gu, I.M. Fuks and Mikael Ciftan, "Grazing Angle Enhanced Backscattering from a Dielectric Film on a Reflecting Metal Substrate", presented at PIERS 2004 in Nanjing, China (2004).

14. Zu-Han Gu, "Enhanced Backscattering from a Dielectric Film on a Reflecting Metal Substrate", presented at PIERS 2004 in Pisa, Italy (2004).

15. Zu-Han Gu, "Speckle Field Correlation for Remote Target Characterization", presented at DARPA/ATO "Speckle Workshop" at Arlington, VA (2005).

16. Zu-Han Gu, "Spectral Redistribution from the Interference of a Collett-Wolf Source," presented at SPIE Annual Meeting in San Diego, CA (2005).

17. Zu-Han Gu, T.A. Leskova, A.A. Maradudin, and Mikael Ciftan, "Pseudo-nondiffraction from the Interference of a Collett-Wolf Source", presented at SPIE Annual Meeting in San Diego, CA (2005).

18. Zu-Han Gu, "Young's Interference Pattern formed with Symmetrical Partially Coherent Sources," presented at SPIE Annual Meeting in San Diego, CA (2005).

19. A.A. Maradudin, E.R. Méndez, and T.A. Leskova, Zu-Han Gu, "One-dimensional Random Surfaces that Display Enhanced Backscattering for One Specified Angle of Incidence", presented at SPIE Annual Meeting in San Diego, CA (2005).

20. Zu-Han Gu, "Young's Interference Pattern Formed with Symmetrical Partially Coherent Sources," presented at PIERS 2005 in Hangzhou, China (2005).

21. Zu-Han Gu, E. Méndez, T.A. Leskova, A.A. Maradudin, and Mikael Ciftan, "Interference of Two Collett-Wolf Beams", presented at PIERS 2005 in Hangzhou, China (2005).

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